

Production of ρ^0 meson with large p_T at NLO in heavy-ion collisions

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Production of ρ^0 meson at high p_T in high-energy nuclear collisions is investigated for the first time at the next-leading-order in the QCD improved parton model. The ρ^0 fragmentation functions (FFs) in vacuum at any scale Q are obtained by evolving through NLO DGLAP equations a newly developed initial parametrization of ρ^0 FFs at a scale $Q_0^2 = 1.5 \text{ GeV}^2$ from a broken $SU(3)$ model. The numerical simulations of p_T spectra of ρ^0 meson in the elementary p + p collisions at NLO give a decent description of STAR p + p data. In A + A reactions the jet quenching effect is taking into account in the higher-twist approach by the effective medium-modified parton FFs due to gluon radiation in the quark-gluon plasma, whose space-time evolution is described by a (3+1D) hydrodynamical model. The nuclear modification factors for ρ^0 meson and its double ratio with π^\pm nuclear modification in central Au + Au collisions at the RHIC are calculated and found to be in good agreement with STAR measurement. Predictions of ρ^0 nuclear modification and the yield ratio ρ^0/π^0 in central Pb+Pb at the LHC are also presented, which shows that the ratio ρ^0/π^0 in central Pb+Pb will approach to that in p+p reactions when $p_T > 12 \text{ GeV}$.

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A new state of matter of deconfined quarks and gluons is expected to be produced in heavy ion collisions (HIC) at very high colliding energies. When an energetic parton produced in the initial hard processes is traveling through this hot/dense QCD medium, a substantial attrition of its energy is observed, which was referred to as jet quenching effect [1, 2]. Even with the development of experiments and theories, di-hadron [3, 4], photon triggered hadron [5, 6] and full jet observable [7–12] emerged to constraint all the model descriptions of the jet quenching patterns, the single inclusive hadron production suppressions, as the most intensively measured and studied observable on jet quenching, is still indispensable to probe the properties of the QCD medium. By comparing the theoretical calculation with the measurements of the production spectra and its suppression of π mesons, i.e, the most commonly observed hadrons, the jet transport coefficient \hat{q} is thus extracted to characterize the local properties of the QCD medium probed by the energetic parton jets [13]. The higher twist multiple scattering model description of the jet quenching incorporated with perturbative quantum chromodynamics(pQCD) improved parton model has successfully described the π^0 and η productions and their suppressions in A + A collisions [14–17].

The study of the identified hadron spectra at high p_T other than π^0 and η in HIC can further constrain and cast insight into the hadron suppression pattern. Whereas a relatively large amount of data on the yields of identified hadrons at large p_T has been accumulated at the RHIC and the LHC [18–20], there are still very few the-

oretical studies of hadrons with different types. An interesting type of identified hadrons with available data is ρ^0 meson, which is heavier than π^0 and η , and also consists of the similar constituent quarks. We notice that even the theoretical calculations of the ρ^0 productions in p + p collisions with large p_T at both the RHIC and the LHC are absent due to the lack of knowledge of parton fragmentation functions (FFs) for ρ_0 in vacuum. In a previous study [16] we have paved the way to understand identified hadron suppression pattern by calculating the productions of η meson and investigating the hadron ratios [16]. In this letter, we extend this study to ρ^0 meson productions and the yield ratios of ρ^0 and π in A + A collisions at the RHIC and the LHC. It is of great interest to see how the alteration of the jet chemistry brought by the jet quenching will eventually affect the ρ^0 production spectrum and the ratio of hadron yields [21–23].

In this paper, firstly we employ a newly developed initial parametrization of ρ^0 FFs in vacuum at a starting low energy scale $Q_0^2 = 1.5 \text{ GeV}^2$, which is included in the $SU(3)$ model fragmentation functions of vector mesons [24, 25]. By evolving them through DGLAP evolution equations at NLO [26], we obtain parton FFs of ρ^0 meson at any hard scale Q . The theoretical results of ρ^0 productions in p + p collisions are provided up to the next-to-leading order(NLO) in pQCD improved parton model, and we find that they describe the experimental data rather well. Then we study ρ^0 production in A + A collisions at both RHIC and LHC by including parton energy loss in the hot/dense QCD medium in the framework of higher twist approach of jet quenching [27, 28]. In this approach, the energy loss due to the multiple scattering suffered by an energetic parton traversing the medium are taken into account by twist-4 processes, and the vacuum fragmentation functions are modified to the effectively

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medium modified ones in high-energy nuclear collisions. Therefore, we can compute numerically for the first time ρ^0 meson yields in A + A collisions. We give a description of ρ^0 nuclear modification factor $R_{AA}(\rho^0)$ at large p_T in Au + Au collisions at the RHIC to confront against the experimental data by STAR Collaboration, and $R_{AA}(\rho^0)$ in Pb + Pb collisions at the LHC to give a theoretical prediction. The double ratio of $R_{AA}(\rho^0)/R_{AA}(\pi^\pm)$ is calculated and found to be in good agreement with the experimental data. Lastly we explore the features of the ρ^0/π^0 ratios in both p+p and A+A collisions.

In NLO pQCD calculation, the single inclusive hadron production can be factorized as the convolution of elementary partonic scattering cross sections $d\hat{\sigma}/d\hat{t}$, parton distribution functions (PDFs) inside the incoming particles and parton FFs to the final state hadrons [29]. In this paper we simplify the formula for further discussion:

$$\frac{1}{p_T} \frac{d\sigma_h}{dp_T} = \int F_q\left(\frac{p_T}{z_h}\right) \cdot D_{q \rightarrow h}(z_h, p_T) \frac{dz_h}{z_h^2} + \int F_g\left(\frac{p_T}{z_h}\right) \cdot D_{g \rightarrow h}(z_h, p_T) \frac{dz_h}{z_h^2}. \quad (1)$$

The above equation implies that the hadron yield in p+p collision will be determined by two factors: the initial (parton-)jet spectrum $F_{q,g}(p_T)$ and the parton fragmentation functions $D_{q,g \rightarrow h}(z_h, p_T)$. In the following calculations, we utilize CTEQ6M parametrization for proton PDFs [30], which has been convoluted with $d\hat{\sigma}/d\hat{t}$ to obtain $F_{q,g}(\frac{p_T}{z_h})$. Here $D_{q,g \rightarrow h}(z_h, p_T)$ represents the vacuum parton FFs, which denote the possibilities of scattered quark or gluon fragmenting into hadron h with momentum fraction z_h . They can be given by corresponding parametrization for different final-state hadrons. So potentially, we could predict all the identified hadron productions in p + p collision as long as the fragmentation functions are available. Note that the factorization scale, renormalization scale and fragmentation scale are usually chosen to be the same and proportional to p_T of the leading hadron in the final-state.

To accurately determine the p + p reference, parton FFs in vacuum as a non-perturbative input, should be available. So far it is still impossible to derive parton FFs from the first-principle of QCD and a common practice is to make phenomenological parametrizations by comparing perturbative QCD calculations with the data. Unlike π and charged hadrons, until now there are very few satisfactory parametrizations of parton FFs for the vector mesons due to the paucity of the relevant data. Fortunately, a broken $SU(3)$ model is recently proposed to provide a systematic description of the vector mesons production [24, 25]. To reduced the complexity of the meson octet fragmentation functions, the $SU(3)$ flavor symmetry is introduced with a symmetry breaking parameter. In addition, isospin and charge conjugation invariance of the vector mesons $\rho(\rho^+, \rho^-, \rho^0)$ are assumed to further reduce independent unknown quark FFs into

functions named valence(V) and sea(γ). The inputs of valence $V(x, Q_0^2)$, sea $\gamma(x, Q_0^2)$ and gluon $D_g(x, Q_0^2)$ FFs are parameterized into a standard polynomial at a starting low energy scale of $Q_0^2 = 1.5 \text{ GeV}^2$ such as:

$$F_i(x) = a_i x^{b_i} (1-x)^{c_i} (1 + d_i x + e_i x^2) \quad (2)$$

These parameters are systematically fixed by fitting the cross section at NLO with the measurements of LEP(ρ, ω) and SLD(ϕ, K^*) at $\sqrt{s} = 91.2 \text{ GeV}$. In Ref. [24, 25] the parameters of ρ^0 FFs in vacuum at $Q^2 = 1.5 \text{ GeV}^2$ are listed and we obtain ρ^0 FFs at any hard scale $D_{q,g}(x, Q^2)$ $Q > 2 \text{ GeV}$ by evolving them through DGLAP evolution equations at NLO with the compute code invented in Ref. [26], then these ρ^0 FFs $D_{q,g}(x, Q^2)$ are used in our numerical simulations.

We observe that ρ^0 FFs are dominated by quark constituents, which is demonstrated by Fig. 1. We have plotted the parton FFs as a functions of fragmenting fraction z_h in the left panel of Fig. 1 at fixed scale of $Q^2 = 100 \text{ GeV}^2$, and also the parton FFs as a functions of final state p_T at fixed fragmenting fraction $z_h = 0.6$ in the right panel of Fig. 1. At the typical $z_h = 0.6$, we notice that the light quark fragmentation function show a rather weak p_T dependence, and the contribution to ρ^0 from quark fragmentation is much larger than that from gluon (or strange quark) fragmentation.

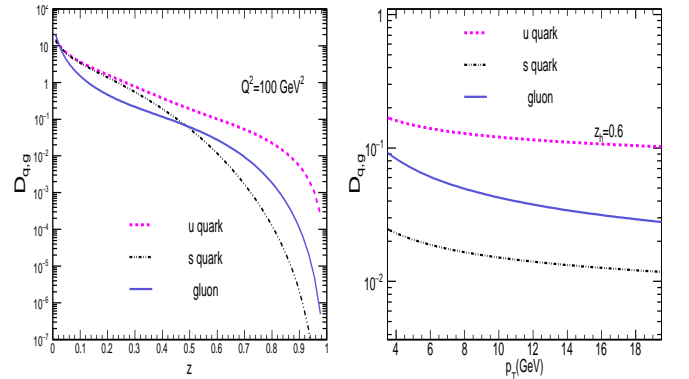


FIG. 1: Left: parton fragmentation functions as a function of p_T at fixed $z_h = 0.6$; Right: parton fragmentation functions as a function of z_h at fixed scale $Q^2 = 100 \text{ GeV}^2$.

The existence of the ρ^0 meson fragmentation functions at NLO allows us to calculate the single inclusive vector meson productions as a function of the final state hadron p_T in pQCD at the accuracy of NLO. Fig. 2 shown the confrontation of the theoretical calculation with the STAR data [18], the results at the scale $\mu = 0.5p_T$ agree well with the data for ρ^0 , thus in the further calculations in nucleus-nucleus collisions, the scales will be fixed to be $0.5p_T$ to provide a fairly good p + p baseline.

A hot and dense QCD matter is created shortly after the high energy central nucleus-nucleus collisions. Be-

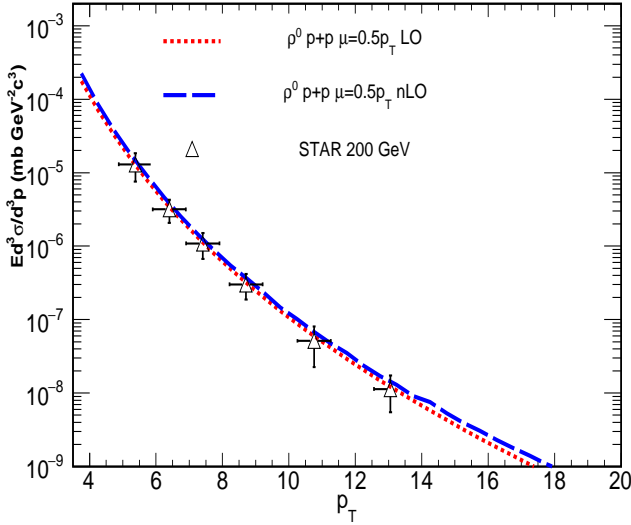


FIG. 2: Numerical calculation of the ρ^0 production in p + p collisions at RHIC 200 GeV comparing with STAR [18] data.

fore a fast parton fragmented into identified hadrons in the vacuum, it should suffer energy loss due to multiple scattering with the parton in medium. In higher twist approach, the multiple scattering is described by twist-4 processes of hard scattering and will lead to effective modification of the vacuum fragmentation functions [14–16]:

$$\begin{aligned} \tilde{D}_q^h(z_h, Q^2) &= D_q^h(z_h, Q^2) + \frac{\alpha_s(Q^2)}{2\pi} \int_0^{Q^2} \frac{d\ell_T^2}{\ell_T^2} \\ &\times \int_{z_h}^1 \frac{dz}{z} \left[\Delta\gamma_{q \rightarrow qg}(z, x, x_L, \ell_T^2) D_q^h\left(\frac{z_h}{z}\right) \right. \\ &\quad \left. + \Delta\gamma_{q \rightarrow gq}(z, x, x_L, \ell_T^2) D_g^h\left(\frac{z_h}{z}\right) \right], \quad (3) \end{aligned}$$

where $\Delta\gamma_{q \rightarrow qg}(z, x, x_L, \ell_T^2)$ and $\Delta\gamma_{q \rightarrow gq}(z, x, x_L, \ell_T^2) = \Delta\gamma_{q \rightarrow qg}(1 - z, x, x_L, \ell_T^2)$ are the medium modified splitting functions [27, 28]. We average the above medium modified fragmentation functions over the initial production position and jet propagation direction, scaled by the number of binary nucleon-nucleon collisions at the impact parameter b in A+A collisions to replace the vacuum fragmentation functions in Eq. (1). We can extract the jet transport parameter \hat{q} from medium modified splitting functions $\Delta\gamma_{q \rightarrow qg, gq}$ mentioned in the above Eq. (3), the \hat{q} is related to the local parton density distribution in the medium when energetic parton jet probed. Therefore the space-time evolution of the medium alter the value of \hat{q} relative to the initial value of it located at the center of the overlap region at initial time of the QGP formation. Product of the four momentum of the jet and the four flow velocity of the medium along the jet propagation path in the collision frame are also included.

The space-time evolutionary informations of the QCD medium are given by a full three-dimensional (3+1D) ideal hydrodynamics description [31, 32]. Parton den-

sity, temperature, fraction of the hadronic phase and the four flow velocity at every time-space points are provided, left only one parameter $\hat{q}_0 \tau_0$, the product of initial value of the jet transport parameter \hat{q}_0 and the time τ_0 when the QCD medium is initially formed. This parameter controls the strength of jet-medium interaction, even furthermore the amount of the energy loss of the energetic jets. In the calculations we use the values of $\hat{q}_0 \tau_0$ in previous studies [14–16], which give very nice description of single π and η productions in HIC. Moreover, we have used the EPS09s parametrization set of nuclear PDFs $f_{a/A}(x_a, \mu^2)$ by considering the initial-state cold nuclear matter effects [33].

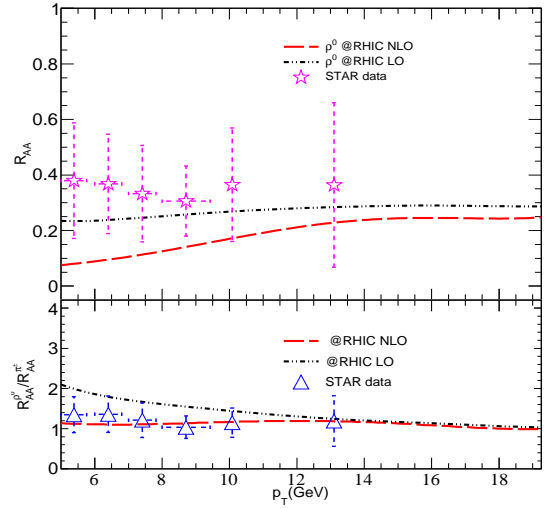


FIG. 3: Top panel: Numerical calculation of the ρ^0 production suppression in 0 – 10% Au + Au collisions at RHIC 200 GeV at both LO and NLO, comparing with STAR [18] data; Bottom panel: double ratio calculation of $R_{AA}^{\rho^0}/R_{AA}^{\pi^+}$ both at LO and NLO, also comparing with STAR data.

With the framework introduced above, we calculate the single inclusive ρ^0 productions in heavy ion collisions up to the NLO. The nuclear modification factor R_{AA} as a function of the final state p_T is therefore calculated to demonstrate the suppression of the production spectrum in A + A collisions relative to that in p + p collision:

$$R_{AB}(b) = \frac{d\sigma_{AB}^h/dy d^2 p_T}{N_{bin}^{AB}(b) d\sigma_{pp}^h/dy d^2 p_T} \quad (4)$$

In the 0 – 10% most central Au + Au collisions at RHIC 200 GeV, we calculate ρ^0 productions at typical values of $\hat{q}_0 = 1.2 \text{ GeV}^2/\text{fm}$ and $\tau_0 = 0.6 \text{ fm}$ at the RHIC [16]. The theoretical calculation can explain the data at large p_T region in the top panel of Fig. 3 for ρ^0 meson. We note that the nuclear suppression factor of ρ^0 is similar to the one for π^0 , as demonstrated by the double ratio

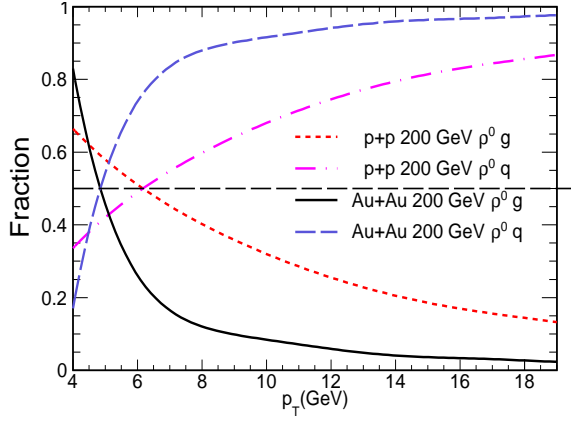


FIG. 4: Gluon and quark contribution fraction of the total yield both in p+p and Au+Au at RHIC

$R_{AA}^{\rho^0}/R_{AA}^{\pi^\pm}$ in the bottom panel of Fig. 3, which is around 1 with results at NLO. In the above plots, we also calculate the case at leading order accuracy which shows a small enhancement at lower p_T .

To understand better the nature of the suppression pattern, we calculate the gluon(quark) contribution fraction of the total yield both in p+p and Au+Au collisions in Fig. 4. It is similar to η and π^0 productions which are dominated by quark fragmentation process contribution at high p_T region either in p+p or in Au+Au (more generally, in A + A), and the jet quenching effect is to suppress the gluon fragmenting contribution but enhance the quark contribution. Therefore the crossing point when the fractional contributions of quark and gluon fragmentations are equal, will move toward lower p_T in Au + Au collision.

We also predict the ρ^0 productions in the 0 – 10% most central Pb + Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV at the LHC in Fig. 5 with typical values of \hat{q}_0 which have been used to describe both productions of single π and η mesons at the LHC [14–16]. We can see with increasing p_T , the nuclear modification factor for ρ^0 meson goes up slowly.

To compare the different trends of π^0 and ρ^0 spectra, we plot the ratio ρ^0/π^0 as a function of the transverse momentum p_T in Fig. 6. One can observe that in p + p collision at RHIC energy and LHC energy, the ratio ρ^0/π^0 increases with the p_T . Though the jet quenching effect may alter the ratio a little bit in A + A at lower p_T , as p_T becomes larger, the ratio in A + A comes very close that in p + p, especially at the LHC with higher p_T .

We note that at high p_T productions of both ρ^0 and π^0 are dominated by quark contribution (for example, see Fig. 4). If at high p_T quark FFs of ρ^0 and π^0 have a

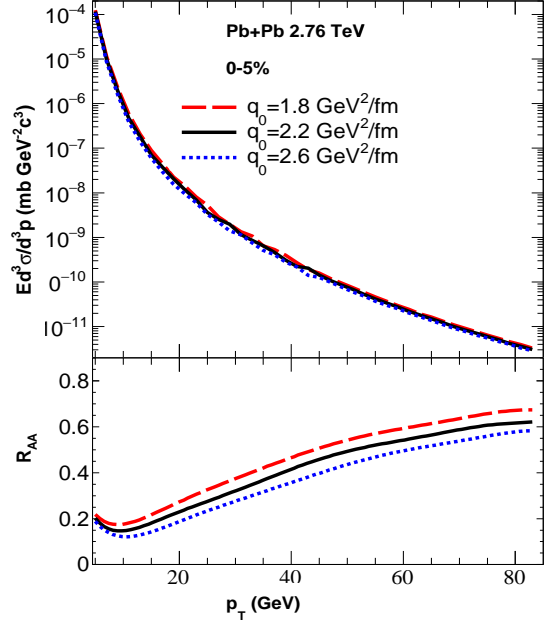


FIG. 5: Numerical prediction of the ρ^0 production in 0 – 10% Pb + Pb collisions at LHC 2.76 GeV

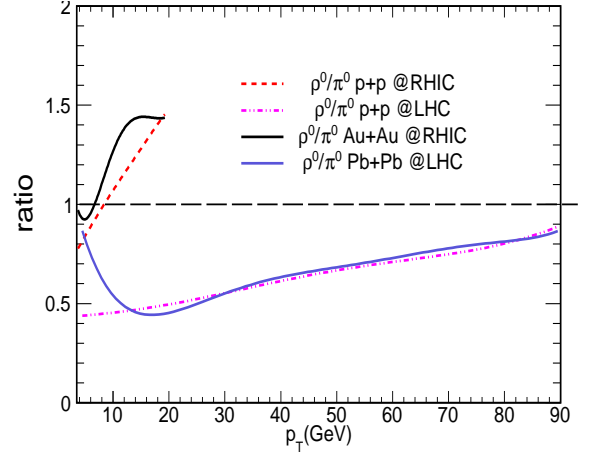


FIG. 6: ρ^0/π^0 production ratio as a function of final state p_T calculated both in p+p and A+A collisions at RHIC and LHC

relatively weak dependence on z_h and p_T , then we have:

$$\begin{aligned} \text{Ratio}(\rho^0/\pi^0) &= \frac{d\sigma_\eta/dp_T}{d\sigma_{\pi^0}/dp_T} \\ &\approx \frac{\int F_q(\frac{p_T}{z_h}) D_{q \rightarrow \rho^0}(z_h, p_T) \frac{dz_h}{z_h^2}}{\int F_q(\frac{p_T}{z_h}) D_{q \rightarrow \pi^0}(z_h, p_T) \frac{dz_h}{z_h^2}} \approx \frac{\Sigma_q D_{q \rightarrow \rho^0}(\langle z_h \rangle, p_T)}{\Sigma_q D_{q \rightarrow \pi^0}(\langle z_h \rangle, p_T)}. \end{aligned}$$

Thus, while quark and gluon may lose different fractions of their energies, at very high p_T region, the ratio ρ^0/π^0 in A + A collisions should approximately be determined only by quark FFs in vacuum with p_T shift because of parton energy loss. As we see quark FFs at large scale

$Q = p_T$ change slowly with z_h and p_T , then the ratio of ρ^0/π^0 in both A + A and p + p may approach to each other, as we have observed in the case for the yield ratio of η/π^0 [16].

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- [1] X. N. Wang and M. Gyulassy, Phys. Rev. Lett. **68**, 1480 (1992).
 - [2] M. Gyulassy, I. Vitev, X. N. Wang and B. W. Zhang, In *Hwa, R.C. (ed.) et al.: Quark gluon plasma* 123-191 [nucl-th/0302077].
 - [3] K. Aamodt *et al.* [ALICE Collaboration], Phys. Rev. Lett. **108**, 092301 (2012) [arXiv:1110.0121 [nucl-ex]].
 - [4] C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **90**, 082302 (2003) [nucl-ex/0210033].
 - [5] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **80**, 024908 (2009) [arXiv:0903.3399 [nucl-ex]].
 - [6] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. C **82**, 034909 (2010) [arXiv:0912.1871 [nucl-ex]].
 - [7] I. Vitev, S. Wicks and B. W. Zhang, JHEP **0811**, 093 (2008) [arXiv:0810.2807 [hep-ph]].
 - [8] I. Vitev and B. W. Zhang, Phys. Rev. Lett. **104**, 132001 (2010) [arXiv:0910.1090 [hep-ph]].
 - [9] W. Dai, I. Vitev and B. W. Zhang, Phys. Rev. Lett. **110**, no. 14, 142001 (2013) [arXiv:1207.5177 [hep-ph]].
 - [10] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. Lett. **105**, 252303 (2010) [arXiv:1011.6182 [hep-ex]].
 - [11] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. C **84**, 024906 (2011) [arXiv:1102.1957 [nucl-ex]].
 - [12] Z. B. Kang, R. Lashof-Regas, G. Ovanesyan, P. Saad and I. Vitev, Phys. Rev. Lett. **114**, no. 9, 092002 (2015) [arXiv:1405.2612 [hep-ph]].
 - [13] K. M. Burke *et al.* [JET Collaboration], Phys. Rev. C **90**, no. 1, 014909 (2014) [arXiv:1312.5003 [nucl-th]]; Z. Q. Liu, H. Zhang, B. W. Zhang and E. Wang, Eur. Phys. J. C **76**, no. 1, 20 (2016) [arXiv:1506.02840 [nucl-th]].
 - [14] X. F. Chen, C. Greiner, E. Wang, X. N. Wang and Z. Xu, Phys. Rev. C **81**, 064908 (2010) [arXiv:1002.1165 [nucl-th]].
 - [15] X. F. Chen, T. Hirano, E. Wang, X. N. Wang and H. Zhang, Phys. Rev. C **84**, 034902 (2011) [arXiv:1102.5614 [nucl-th]].
 - [16] W. Dai, X. F. Chen, B. W. Zhang and E. Wang, Phys. Lett. B **750**, 390 (2015) [arXiv:1506.00838 [nucl-th]].
 - [17] W. Dai and B. W. Zhang, arXiv:1612.05848 [hep-ph].
 - [18] G. Agakishiev *et al.* [STAR Collaboration], Phys. Rev. Lett. **108**, 072302 (2012) [arXiv:1110.0579 [nucl-ex]].
 - [19] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **83**, 024909 (2011) [arXiv:1004.3532 [nucl-ex]].
 - [20] R. Bala, I. Bautista, J. Bielcikova and A. Ortiz, Int. J. Mod. Phys. E **25**, no. 07, 1642006 (2016) [arXiv:1605.03939 [hep-ex]].
 - [21] W. Liu, C. M. Ko and B. W. Zhang, Phys. Rev. C **75**, 051901 (2007) [nucl-th/0607047].
 - [22] S. J. Brodsky and A. Sickles, Phys. Lett. B **668**, 111 (2008) [arXiv:0804.4608 [hep-ph]].
 - [23] X. Chen, H. Zhang, B. W. Zhang and E. Wang, J. Phys. **37**, 015004 (2010) [arXiv:0806.0556 [hep-ph]].
 - [24] H. Saveetha, D. Indumathi and S. Mitra, Int. J. Mod. Phys. A **29**, no. 07, 1450049 (2014) [arXiv:1309.2134 [hep-ph]].
 - [25] D. Indumathi and H. Saveetha, Int. J. Mod. Phys. A **27**, 1250103 (2012) [arXiv:1102.5594 [hep-ph]].
 - [26] M. Hirai and S. Kumano, Comput. Phys. Commun. **183**, 1002 (2012) [arXiv:1106.1553 [hep-ph]].
 - [27] X. f. Guo and X. N. Wang, Phys. Rev. Lett. **85**, 3591 (2000) [hep-ph/0005044].
 - [28] B. W. Zhang and X. N. Wang, Nucl. Phys. A **720**, 429 (2003) [arXiv:hep-ph/0301195].
 - [29] J. F. Owens, Rev. Mod. Phys. **59**, 465 (1987).
 - [30] H. L. Lai *et al.* [CTEQ Collaboration], Eur. Phys. J. C **12**, 375 (2000) [hep-ph/9903282].
 - [31] T. Hirano, Phys. Rev. C **65**, 011901 (2002).
 - [32] T. Hirano and K. Tsuda, Phys. Rev. C **66**, 054905 (2002).
 - [33] K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP **0904**, 065 (2009) [arXiv:0902.4154 [hep-ph]].
 - [34] T. Richer [ALICE Collaboration], arXiv:1505.04717 [hep-ex].